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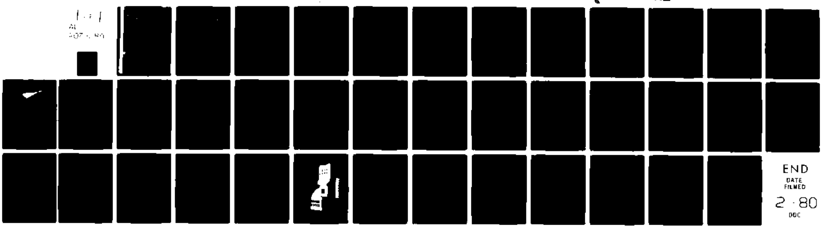

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DEVELOPMENT OF A COLOR ALPHANUMERIC LIQUID CRYSTAL DISPLAY

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December 1979

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This report encompasses efforts directed toward the development of a Multicolor liquid crystal display suitable for aircraft command and control applications.

The approach taken was to combine a striped, color selective filter with previously developed matrix liquid crystal display technology. Two 1.75 x 1.75 inch displays and one set of LSI drive circuits were constructed.

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The displays provided 100 elements per inch horizontal resolution and 33 elements per inch vertical resoltuion, with each vertical element consisting of a red-green-blue triad. While the optical performance of the displays was limited, sufficient information was gained to ensure adequate viewability in subsequent designs.

PREFACE

This final report covers the work accomplished during the period 1 October 1977 through 30 May 1979 under Contract N62269-77-C-0477, Color Alphanumeric Liquid Crystal Display. This program is under the technical direction of Mr. Karl Quiring of the Naval Air Development Center, Warminster, Pennsylvania.

The work was accomplished by the Display Systems Laboratory under the direction of Mr. J. Gunther who was Project Manager and contributed the material on Filter Selection and Display Performance Evaluation.

Special acknowledgement is given to the following individuals and organizations who contributed to the project:

The Liquid Crystal Products Department of the Industrial Products Division manufactured the matrix display and integrated drivers under the direction of Dr. L. Lipton.

Mr. W. C. Hoffman and Mr. W. R. Lichty acted as consultants to the program and provided the editing support in the preparation of this report.

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SECTION 1

INTRODUCTION AND SUMMARY

The rapidly increasing number of aircraft avionics systems have resulted in numerous readouts and monitoring panels in scattered locations of the cockpit. At the present time, most of these readouts are abbreviated identifications backlighted by incandescent bulbs, or simple numeric indicators. Advanced aircraft systems designs, such as AIDS, will incorporate a data processing and display system designed to provide an air crew with an integrated presentation of warning, functional status, mode advisory, and auxiliary data on a single display surface. The advantages of the use of color to categorize this type of information have long been recognized. However, the application of color displays to aircraft cockpits is, with some exceptions, still awaiting the development of a highly reliable, easily visible color display technology. The Color Alphanumeric Liquid Crystal Display contract was performed under contract number N62269-77-C-0477 for the Naval Air Development Center. The effort was directed towards the development of a multicolor display, suitable for aircraft command and control applications, through the combination of a striped, color selective filter with previously developed liquid crystal matrix display technology.

Since the construction of the liquid crystal display is similar to devices previously developed, the design phase of this program concentrated on the selection of the required color filter. Analysis indicated that the filter must be in intimate contact with the liquid crystal material to avoid parallax and degradation of color purity. Therefore, the compatibility of the filter with the liquid crystal display materials and processes was equally as important as color purity, transmission, and other optical characteristics. A trade-off study was performed and a multilayer dielectric filter on the inside of the display cover glass was selected for ease of fabrication, compatibility with display processing, and high transmission.

A total of three color displays were constructed. Each display had a viewing area of 1.75 x 1.75 inches, with 100 elements per inch horizontal resolution and 33 red-green-blue triads per inch vertical resolution. The first, using a sample filter with only red stripes, was built to confirm the manual technique used to align the filter stripes with the matrix elements.

The next display was assembled with a three color filter. However, this display had poor performance, due to an error in the filter design and to a reduction in the scattering performance of the liquid crystal material caused by an adverse reaction with the filter materials. The final display incorporated two improvements over the previous device. First, the cell filling technique was changed to eliminate the use of room temperature curing epoxy (which may have contributed to the poor performance of the second display); and, second, a thin-film contamination prevention barrier, developed on a Hughes sponsored liquid crystal light valve program, was deposited between the filter and the liquid crystal material. Unfortunately, an error was made during the deposition of this barrier, and the resulting film was full of bubbles. Since these bubbles scatter ambient light independent of the electric potentials applied to the display picture elements, the contrast and color purity of the final display, as summarized in Table 1, were much lower than the design goals.

While neither of the three-color displays constructed on this program demonstrated the performance necessary for cockpit applications, this effort has demonstrated the following positive results: First, the technology exists to produce three-color striped filters and to align and assemble the

TABLE 1. COLOR ALPHANUMERIC LIQUID CRYSTAL DISPLAY PERFORMANCE

	Design Goal			Actual		
	Red	Green	Blue	Red	Green	Blue
Luminance, fL(1)	450	700	450	1620	1080	1100
Contrast Ratio(1)	6	9	6	1.59	1.06	1.08
Color Furity, %	80	70	70	50	20	30
Dominant Wavelength, nm	600	540	480	610	610	535C

Note (1) 10,000 fc ambient, viewed at a 30° angle to the specular reflection of the ambient source. Contrast is independent of magnitude of ambient illumination.

filters into matrix liquid crystal displays; Second, the basic concept of the color liquid crystal display using a striped filter is successful, although both the filter and contamination barrier designs require improvement; and, Third, the combining of primary colors (for example, combining red and green to produce yellow characters) works well for the 0.01 inch stripe widths and 30 inch viewing distance used in these devices.

SECTION 2

DISPLAY DEVICE DESIGN

The goal of the Color Alphanumeric Liquid Crystal Display program was to develop a multicolor display for cockpit applications by combining a color selective filter with existing matrix liquid crystal display technology. This section includes a brief review of the baseline technology, and a discussion of the filter design rationale.

BASELINE TECHNOLOGY

The matrix liquid crystal display technology dates to September 1973, when the first video liquid crystal display was demonstrated. A 100 x 100 element, one inch square, defect free device was built in June of 1975. In December of the same year, a two inch square "quad" display, constructed of four one inch chips, was demonstrated. In November of 1977, the first 175 x 175 element, 1.75 inch square display was completed. This device used essentially the same design, except for the color filter, as the displays built during this contract.

Figure 1 illustrates the construction of a matrix liquid crystal display. The liquid crystal material is sandwiched between a cover glass coated with a transparent electrode, and a semiconductor chip. The surface of this chip is covered with an array of highly reflective electrodes. This chip also contains one storage capacitor and one switching field effect transistor for each display element, and row and column bus electrodes. The column busses connect to the drains of every transistor in their respective columns. Similarly, one row electrode connects to the gate of each transistor in the corresponding row. Line-at-a-time addressing is used to form an image on the display. To write one line, voltages proportional to the amplitudes of each element are placed on the column electrodes. A voltage is applied to the appropriate row electrode, the transistors in the row conduct, and each elemental storage capacitor charges to the voltage applied to the corresponding column electrode. The storage capacitors hold sufficient charge to energize the liquid crystal layer until the row is rewritten during normal 30 or 60 hertz refresh.

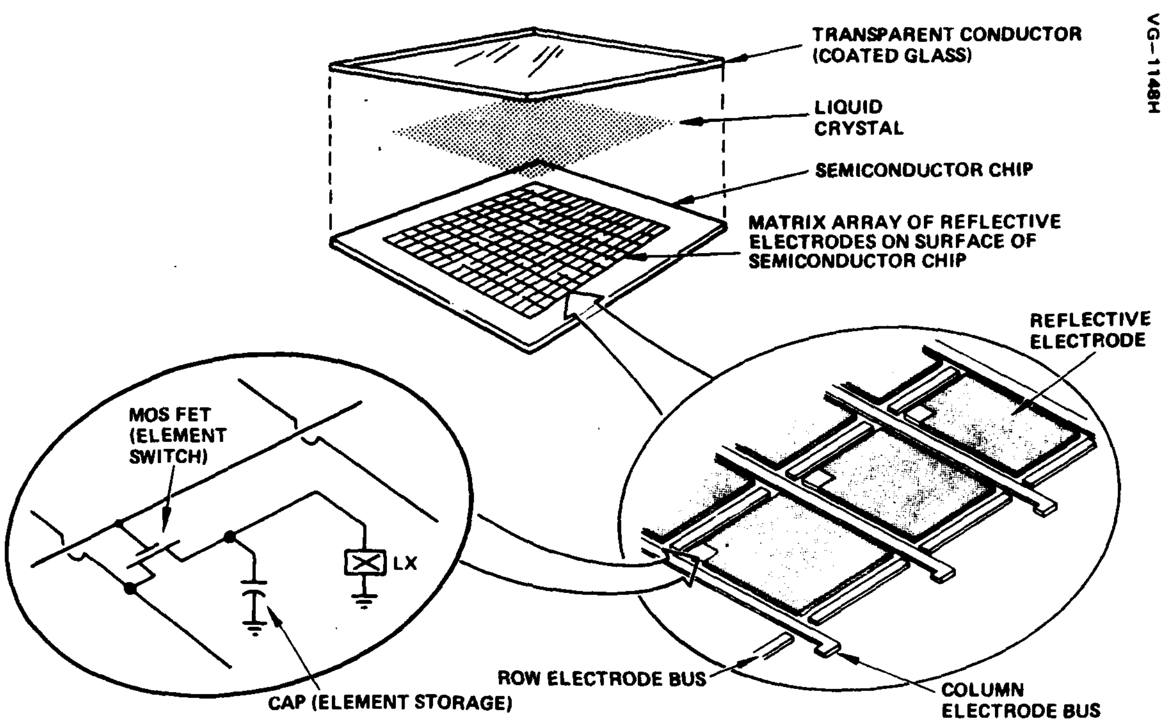

Figure 1. Matrix liquid crystal display construction.

The liquid crystal material in the display described above modulates ambient illumination by dynamic scattering. With no voltage applied to the liquid crystal layer, the material is clear, and ambient light is specularly reflected from the mirror electrodes. With a voltage applied, the liquid crystal layer becomes turbid and scatters the reflected ambient light. A dynamic scattering mode display is generally viewed with a light trap, as shown in Figure 2. The positions of the display, light trap, and observer are established such that the observer sees only the reflection of the black light trap where no voltage is applied to the display elements. The elements where a voltage is applied scatter ambient illumination towards the observer. Thus, the scattering elements appear bright on a dark background.

The circuitry required to interface a line-at-a-time addressed display, such as a matrix liquid crystal display, with a composite video source is illustrated in Figure 3. A serial to parallel converter (which may be analog or digital, depending on the nature of the displayed image) takes one sample

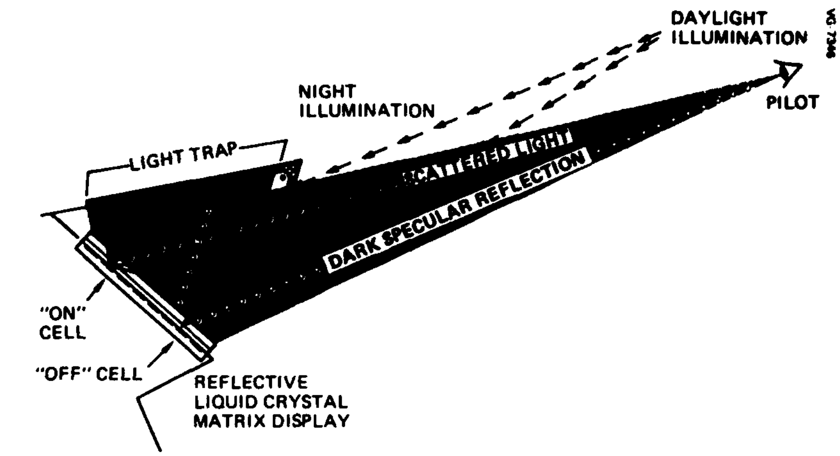

Figure 2. Dynamic scattering liquid crystal display viewing conditions.

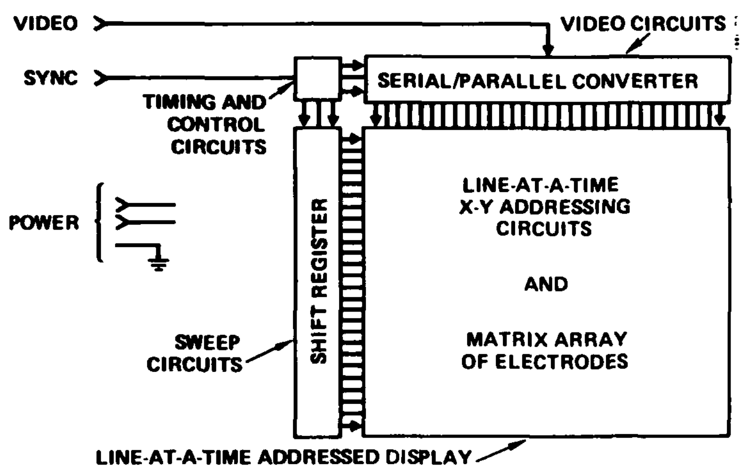

Figure 3. Functional blocks and electrical interface.

of the input video line for each column of the display. The sampling circuits are double buffered so that one video line is sampled while the previous input line is transferred to the display storage capacitors. A sweep shift register enables the rows of the display successively in synchronism with the input video signal. The video and sweep circuitry for a 175 x 175 element matrix liquid crystal display is packaged in 13 large scale integrated (LSI) circuits. A few additional IC packages and discrete components are necessary for timing and control functions.

FILTER DESIGN

The problem of selecting a filter to provide an optimal combination of dominant wavelength, photopically weighted transmission, and color purity has been extensively studied[1,2]. The results of this study show that transmission increases and purity decreases with increasing filter passband width, and that both transmission and purity change as a function of dominant wavelength. The relationships between dominant wavelength and purity, called the MacAdam limits, are plotted in Figure 4 for three values of luminous transmission[3].

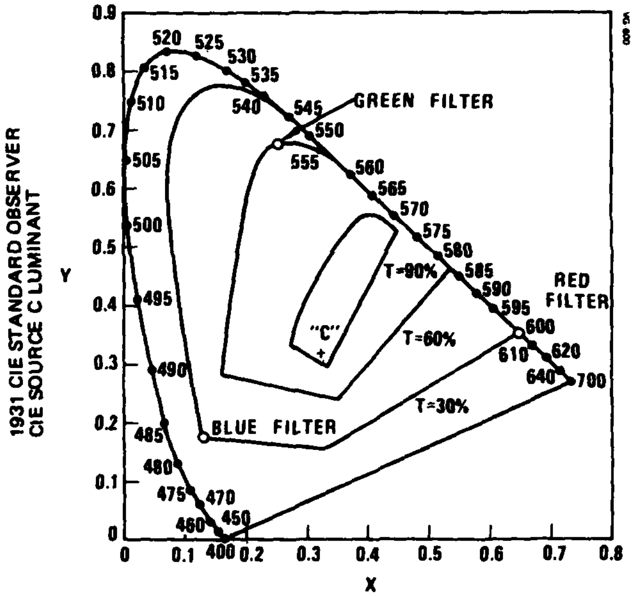

Figure 4. Chromaticity LOCI of optimal colors as a function of luminous transmission (T).[3]

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1. Mac Adam, P. L., The Theory of the Maximum Visual Efficiency of Colored Materials, Journal of the Optical Society of America, 25, 249 (1935).
2. Mac Adam, P. L., Maximum Visual Efficiency of Colored Materials, Journal of the Optical Society of America, 25, 361 (1935).
3. Wyszecki, G., and Stiles, W. S., Color Science, John Wiley and Sons, New York, 1967, p. 341.

Figure 4 also shows the chromaticity coordinates desired for the Color Alphanumeric Display. They were selected at the "corners" of the Mac Adam limits to provide maximum chromatic separation between the three hues. Once the coordinates had been selected, Mac Adam's data provided "ideal" spectral transmission characteristics for the required filters. These characteristics are plotted in Figure 5a.

The three approaches considered were, first, multilayer dielectric interference filter located on the display cell cover glass; second, an absorptive filter, also located on the cover glass; and, third, a multilayer dielectric mirror fabricated on the silicon matrix addressing chip in lieu of the usual metal mirror electrodes. They were evaluated for spectral characteristics and compatibility with the liquid matrix display materials and processes, as follows:

Spectral Characteristics

The spectral transmission or reflectance characteristics, extrapolated from manufacturer's data on stock filters, of the three approaches are plotted in Figures 5b, c, and d, respectively. The interference and absorptive filters are roughly equivalent, with the former having sharper edge slopes and the latter providing slightly higher peak transmission. Note that the transmissions given for both are for two passes through the filters. The dielectric mirror would be fabricated in lieu of the usual metallic mirror, which has a reflectance of 70 percent. Thus, compared to a filter of 60 percent transmission, the dielectric mirror provides a factor of $0.90/(0.6 \times 0.7) = 2.1$ more brightness. However, the three-layer mirror illustrated has a wide bandwidth and unacceptable color purity. Increasing the number of layers would increase the peak reflectance and reduce the bandwidth, at the expense of increased risk. Both the interference filter and the dielectric mirror have some specular shift with incidence angle.

Compatibility with Display Materials and Processes

The original concept for the construction of the Color Alphanumeric Liquid Crystal Display was to fabricate the filter on a glass faceplate and then laminate an extremely thin piece of transparent-electrode-coated glass

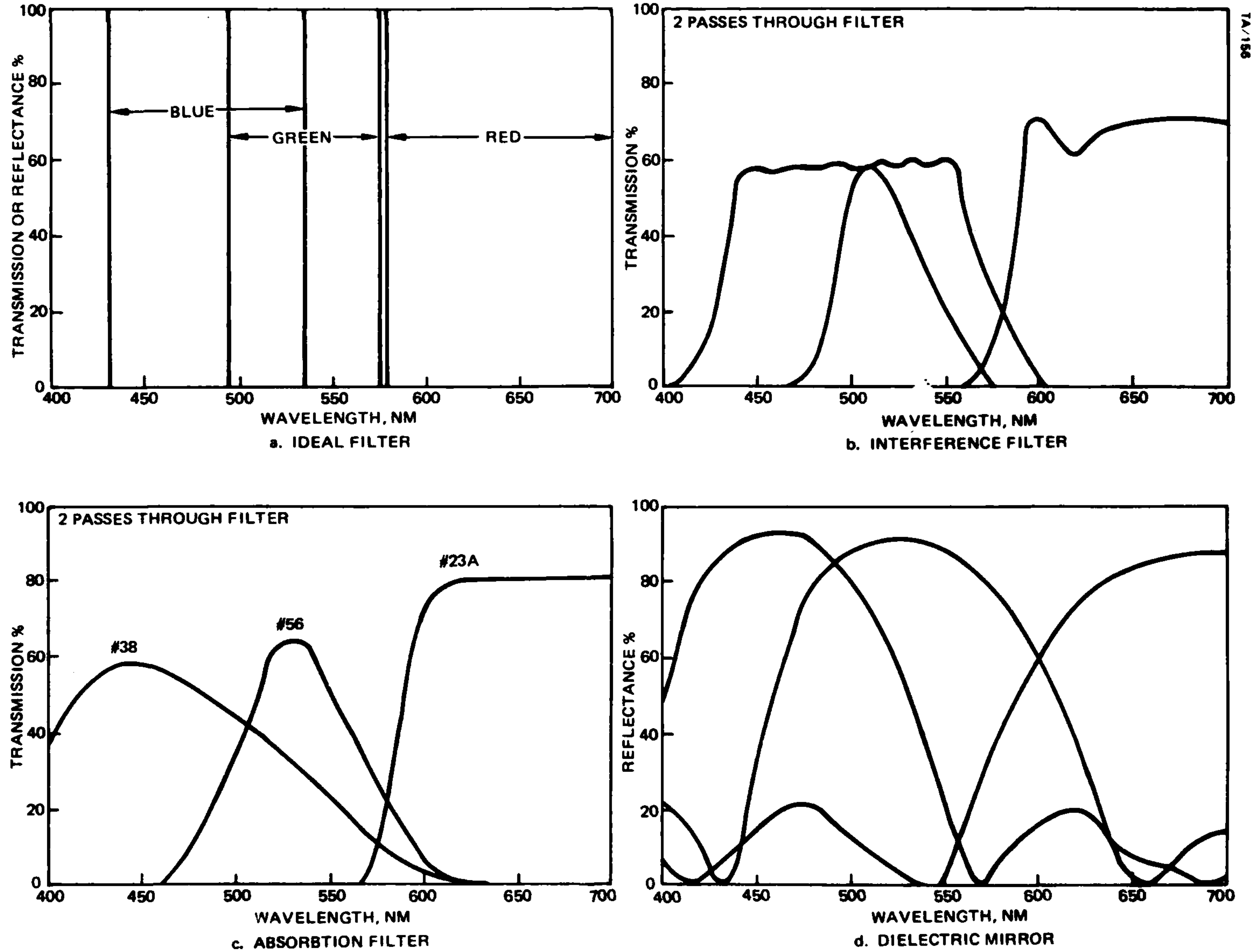

Figure 5. Filter spectral transmission/reflectance characteristics.

to the filter. With this assembly technique, the filter would not be subjected to the high temperature vacuum process used to deposit the transparent electrode. Unfortunately, the use of a spacer between the filter and the liquid crystal layer results in a severe degradation of color purity, as shown in Figure 6. This figure illustrates a typical viewing condition, with the ambient light incident at 30° from normal, and the observer viewing at 15° to the normal. Although the liquid crystal material scattering occurs behind a red filter stripe, 14 percent of the light reaching the observer has passed twice through the adjacent green stripe. An additional 14 percent has passed once through both the green and red filters. The observer, depending on distance

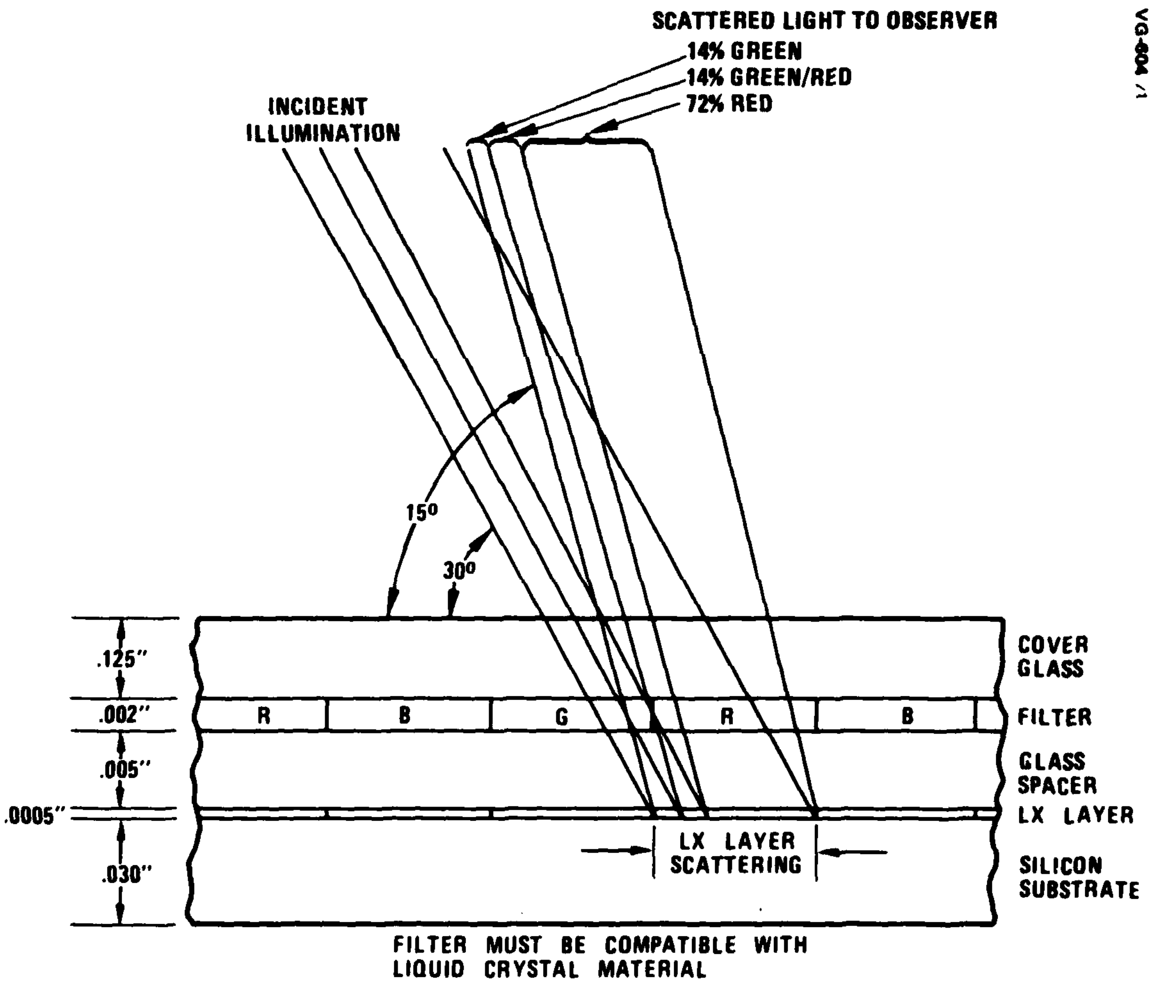

Figure 6. Loss of color purity caused by spacer.

from the display, would see either a rainbow effect, or a yellow-orange color instead of the desired red. Therefore, the filter or mirror must be in intimate contact with the liquid crystal material and the transparent electrode. Additionally, it must be able to tolerate temperatures of 200°C in vacuum during transparent electrode deposition and 100°C in air for several hours during cell assembly.

The dielectric mirror and the interference filter are both constructed of thin films deposited under vacuum and capable of withstanding temperatures well in excess of 200°. Thus, both are compatible with the electrode deposition and cell assembly processes. The dielectric mirror could be made with materials already present on the matrix addressing IC, and would be completely compatible with the liquid crystal material. The interference filter would be fabricated with two relatively stable inorganic compounds. However, there is some risk of adverse interaction between these compounds and the liquid crystal material. Few, if any, organic absorption filter materials could tolerate the high temperature vacuum deposition process. Stable, inorganic absorption materials may exist, but no information on candidate compounds was readily available. Thus, the availability of absorptive filter meeting all the spectral transmission and process compatibility requirements could not be ascertained, and this candidate approach was eliminated.

Technical Risk

Of the two remaining approaches, the interference filter had much lower technical risk, since striped filters of this type are in wide use in single-tube color vidicon cameras. The dielectric mirror, on the other hand, has two major technical problems. First, while the deposition processes for the materials in question are straightforward, the photolithographic processes to pattern the stripes require development. Second, some provision for electrical connection to the liquid crystal material must be made, either by making the mirror from slightly conductive materials, or by using a conductive film on top of the mirror with openings through the mirror for electrical contact to the drive circuitry. While both of these problems are undoubtedly solvable, the technical risk is very high for the present program.

Table 2 is a summary of the tradeoffs between the three candidate approaches. The interference filter was selected for good optical performance, compatibility with existing processes, probable compatibility with the liquid crystal material and lowest technical risk.

PERFORMANCE PROJECTION

The performance of a black-and-white dynamic scattering matrix display is summarized in Figure 7, which shows diffuse reflectance and contrast ratio as a function of viewing angle. Given this data and the interference filter characteristics from Table 2, the predicted performance of the Color Alphanumeric Liquid Crystal Display can be calculated. Assuming a viewing condition where the observer views the display at normal incidence, and the ambient illumination is from 30 degrees off normal, Figure 7 indicates an expected reflectance of 60 percent of Lambertian and a contrast ratio of 19.

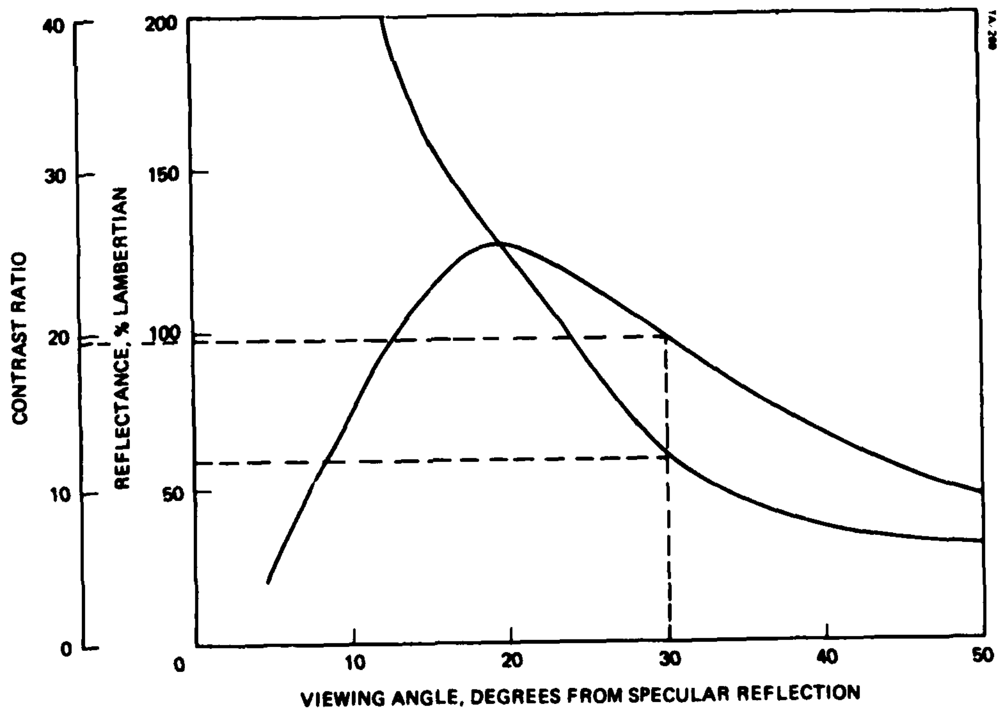

Figure 7. Matrix display scattering performance

TABLE 2. FILTER TRADEOFF STUDY SUMMARY

	Ideal Characteristics			Interference Filter			Absorptive Filter			Dielectric Mirror		
	R	G	B	R	G	B	R	G	B	R	G	B
Luminous Transmission, %	30	60	30	20	33	20	30	34	20	28	75	30
Dominant Wavelength, nm	605	540	480	605	540	485	600	540	480	610	545	480
Purity, %	100	80	80	100	76	71	100	70	62	54	30	62
Angular Sensitivity	None			~3% λ shift at 30^{o}			None			Slight		
Process Compatible	Yes			Yes			No			Yes		
LX Material Compatible	Yes			Probably			Unlikely			Yes		
Technical Risk	Low			Low			High			High		
Rating	Acceptable			Selected			Unacceptable			Unacceptable		

The reflectance (relative to Lambertian) of a red dot on the display can then be calculated for the "on" and "off" states, as follows:

$$R_{on} = \text{(Black and White Display Reflectivity) (Red Filter Transmission)}$$

$$= 0.60 \times 0.20 = 0.12,$$

and

$$R_{off} = R_{on}/\text{(Black and White Display Contrast)}$$

$$= 0.12/19 = 0.0063$$

Similarly,

$$G_{on} = 0.198,$$

$$G_{off} = 0.010,$$

$$B_{on} = 0.12, \text{ and}$$

$$B_{off} = 0.0063.$$

However, since this display is intended for viewing at a distance where individual stripes are not resolved, the brightness and contrast perceived by an observer are determined by the average reflectances of the red, green, and blue stripes forming a resolution element. Given an ambient illumination level I, the brightness of a red symbol (B_R) is given by

$$B_R = I\frac{(R_{on} + G_{off} + B_{off})}{3},$$

and the contrast (C_R) is given by

$$C_R = \frac{(R_{on} + G_{off} + B_{off})}{(R_{off} + G_{off} + B_{off})} .$$

Additionally, the chromaticity of a symbol is also a function of all three colors and can be calculated using standard techniques. The calculated predicted performance of the Multicolor Liquid Crystal Display is summarized in Table 3.

TABLE 3. PREDICTED DISPLAY PERFORMANCE WITH PREDICTED FILTER CHARACTERISTICS

Color	Brightness 10^4 fc Ambient, fL	Contrast Ratio	Dominant Wavelength, nm	Color Purity %
Red	454	6.0	600	80
Green	702	9.3	540	70
Blue	454	6.0	480	70
Red + Green	1081	14.4	575	80
Green + Blue	1081	14.4	490	40
Red + Blue	833	11.1	555C	35
Red + Blue + Green	1460	19.0	510	10

SECTION 3

DISPLAY CONSTRUCTION AND EVALUATION

Three 175 x 175 element, 100 element per inch matrix liquid crystal displays were fabricated during this program. The first was assembled using a faceplate with only red filter stripes to test the procedure for aligning the filter with the rows of the matrix of display elements. The second and third displays contained three-color striped filters. The second display did not function properly, and several improvements were incorporated into the third device.

The following section's will discuss display assembly, measured filter characteristics, and performance evaluation.

DISPLAY ASSEMBLY

The first display device constructed on this program was intended to test the assembly processes and the method for aligning the filter stripe with the rows of the matrix of display elements. The following procedure was used:

1. The filter, consisting of only red stripes, was fabricated on a pyrex cover glass.
2. An indium-tin-oxide transparent electrode was deposited directly onto the filter.
3. The cover glass was manually registered with the silicon matrix addressing chip (previously mounted to a glass substrate), with an epoxy-coated mylar spacer around the perimeter of the display between the cover and the silicon chip. After registration, the assembly was clamped in a simple spring-loaded fixture and the epoxy was cured at 100 degrees centigrade.
4. The liquid crystal was introduced into the display through gaps in the mylar spacer, which were then sealed with a room-temperature-setting epoxy.

On the initial trial, this procedure produced rather poor alignment, as shown in figure 8a. At the right side of the display, the filter stripe and the matrix array were misregistered by 0.0015 inch (15 percent of an element height). However, after a review of the procedure, the conclusion was reached that acceptable alignment was possible in subsequent devices.

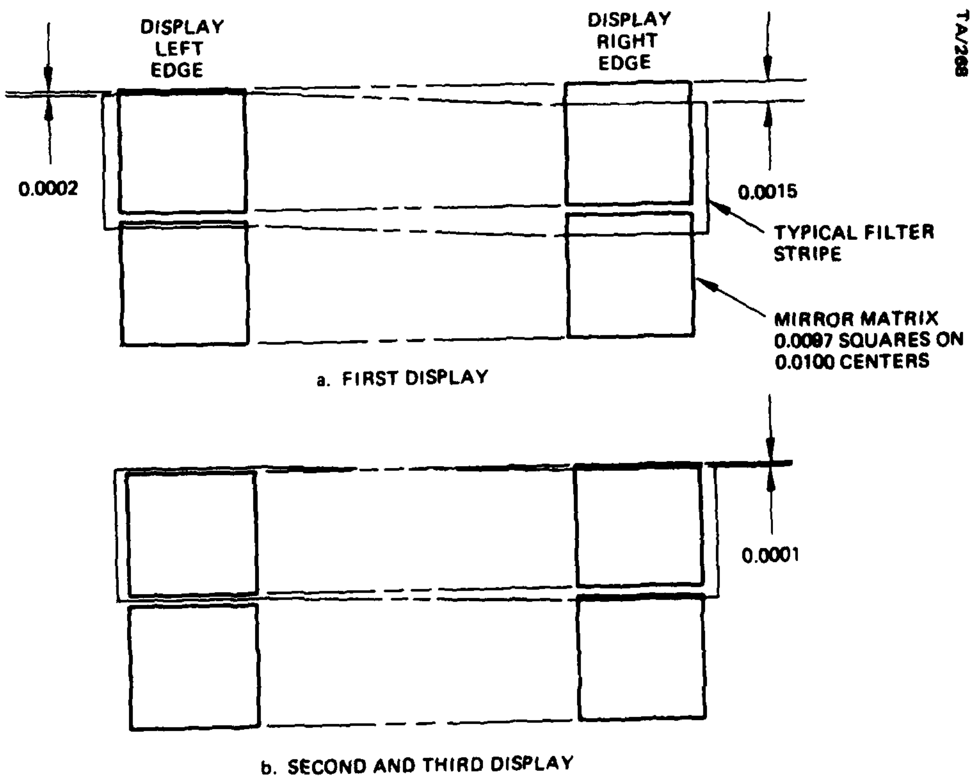

Figure 8. Filter Stripe Registration.

The same procedure was used to assemble the second display device, except that the filter had all three color stripes. The resulting registration was excellent, as shown in Figure 8b. The worst-case error was roughly 1 percent of an element height. Unfortunately, the liquid crystal material in this device did not scatter properly, due, to an adverse reaction with the color filter materials and (possibly) the room-temperature-setting epoxy sealant.

Therefore, two major changes were incorporated into the third display. First, a top fill technique was used to eliminate room temperature epoxy. The liquid crystal material was introduced to the cell through tapered holes drilled in two corners of the cover glass; these holes were then sealed with indium plugs. Second, an anticontamination barrier was deposited on the filter prior to deposition of the transparent electrode. This barrier, originally developed for a similar purpose on a Hughes sponsored liquid crystal light valve program, is a five-micron-thick film of chemically inert, optically transparent material which prevents interaction between the liquid crystal and the filter components.

Prior to depositing the anticontamination barrier on the remaining three-color filters, trial depositions were made on sample filters without significant degradation of their optical performance. Unfortunately a processing error was made during the final deposition, causing bubbles in the barrier layer deposited on the three-color filters. These bubbles, which scatter incident illumination and ruin the display contrast, were not discovered until the third display was completed and evaluated. Thus, although the liquid crystal material scatters well, the performance of the final display was very poor.

FILTER CHARACTERISTICS

The three color striped filters used in this program were fabricated by Optoline Corporation of North Andover, Massachusetts, who also provided witness plates for each color. The witness plates have transmission characteristics identical to those of their respective color stripe, since both are

fabricated during the same deposition cycle. The transmission of these plates was measured at zero degrees incidence for all three colors and the resulting data is plotted in Figures 9a, 10a, and 11a. The transmissions of the red and blue filters at 0 degrees incidence are a good approximation of the ideal characteristics. However, the transmittance peak of the green filter is narrower than desired, due to a flaw in the deposition cycle. While this problem would not occur in the manufacture of subsequent filters, program constraints did not allow fabrication of a second set.

The transmissions were also measured at 0° and 30° incidence after the deposition of the contamination barrier that was used in the third display to prevent interaction between the filter and liquid crystal materials. In all cases, the effect of the coating was to shift the transmission curves to the left as shown in Figures 9b-11b. Since the thin film contamination prevention barrier used was slightly yellow in tint, not clear as desired, noticeable attenuation also occurred in the case of the blue and green filters. Convoluting these curves with that of the human eyes shows that the spectral shift caused by the coating would allow the red to be perceived far more easily than either green or blue. In addition to the spectral shift caused by this coating, a further shift occurred at increased incidence angle. This is an inherent feature of interference filters that, unfortunately, was not compensated for in the specification provided to the filter manufacturer. The transmission of the filter at 30° incidence is shown in Figures 9c-11c.

The effects of this oversight are illustrated in Figures 9d-11d, which show the calculated two pass transmission of the filters in front of a diffuse reflector with illumination at normal incidence and observation from 30 degrees off normal. These figures also show the predicted characteristics used in the design phase of the program. The net effect is to shift all three colors toward the shorter wavelengths and to radically reduce the luminous transmission of the blue and green stripes, as summarized in Table 4. Using these measured filter transmissions, the display performance projections were recalculated and are summarized in Table 5.

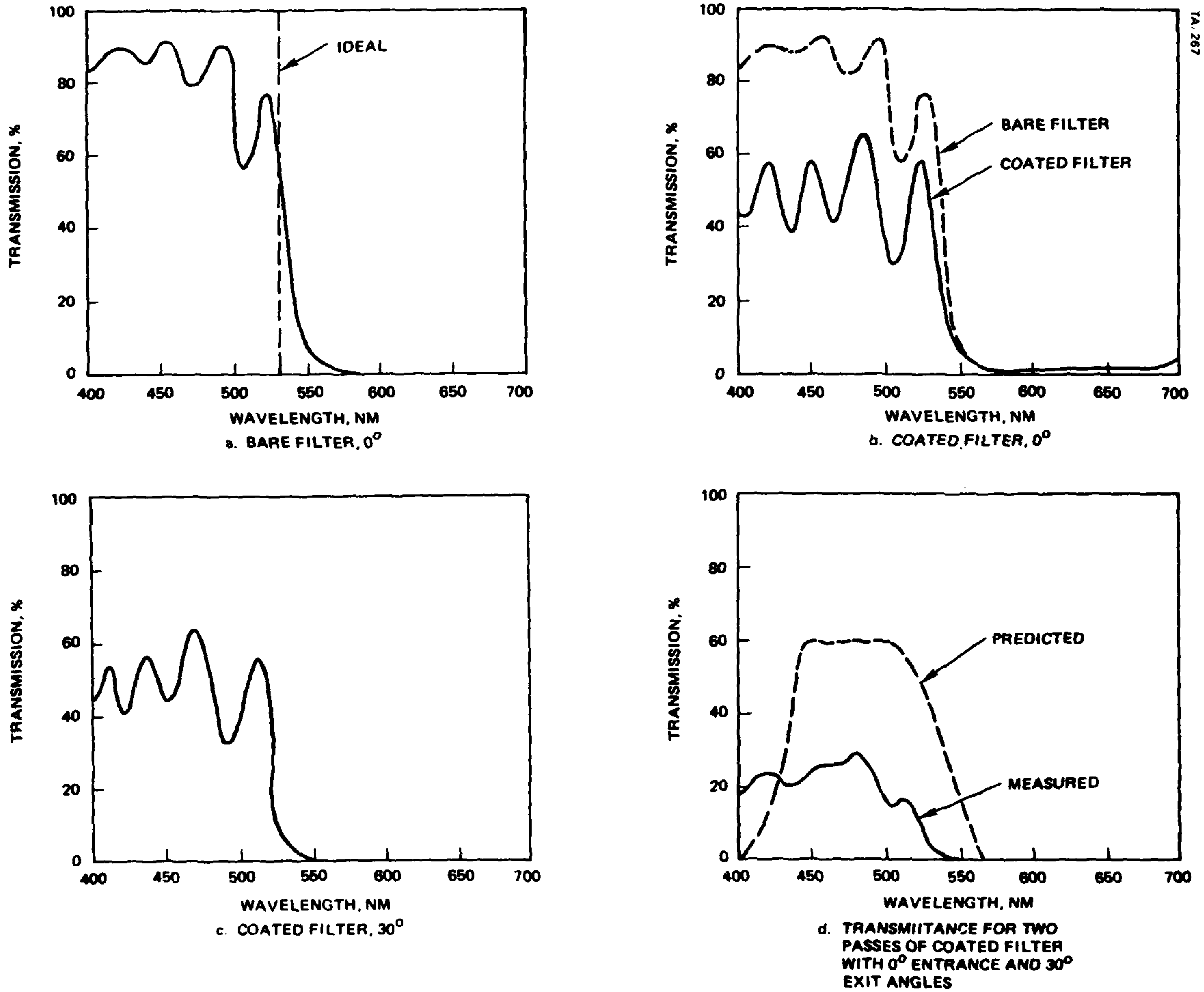

Figure 9. Spectral transmission of blue filter stripe.

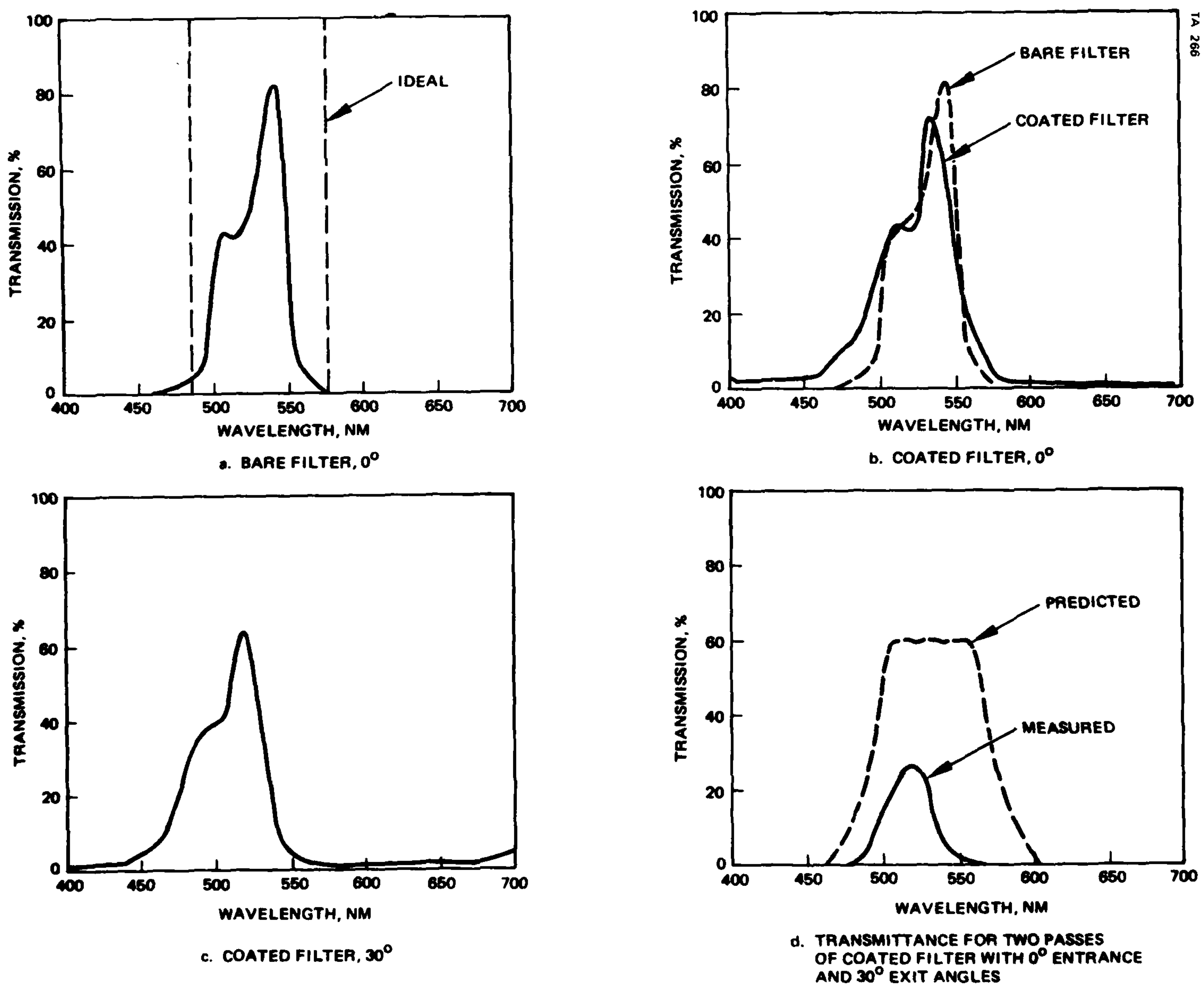

Figure 10. Spectral transmission of green filter stripe.

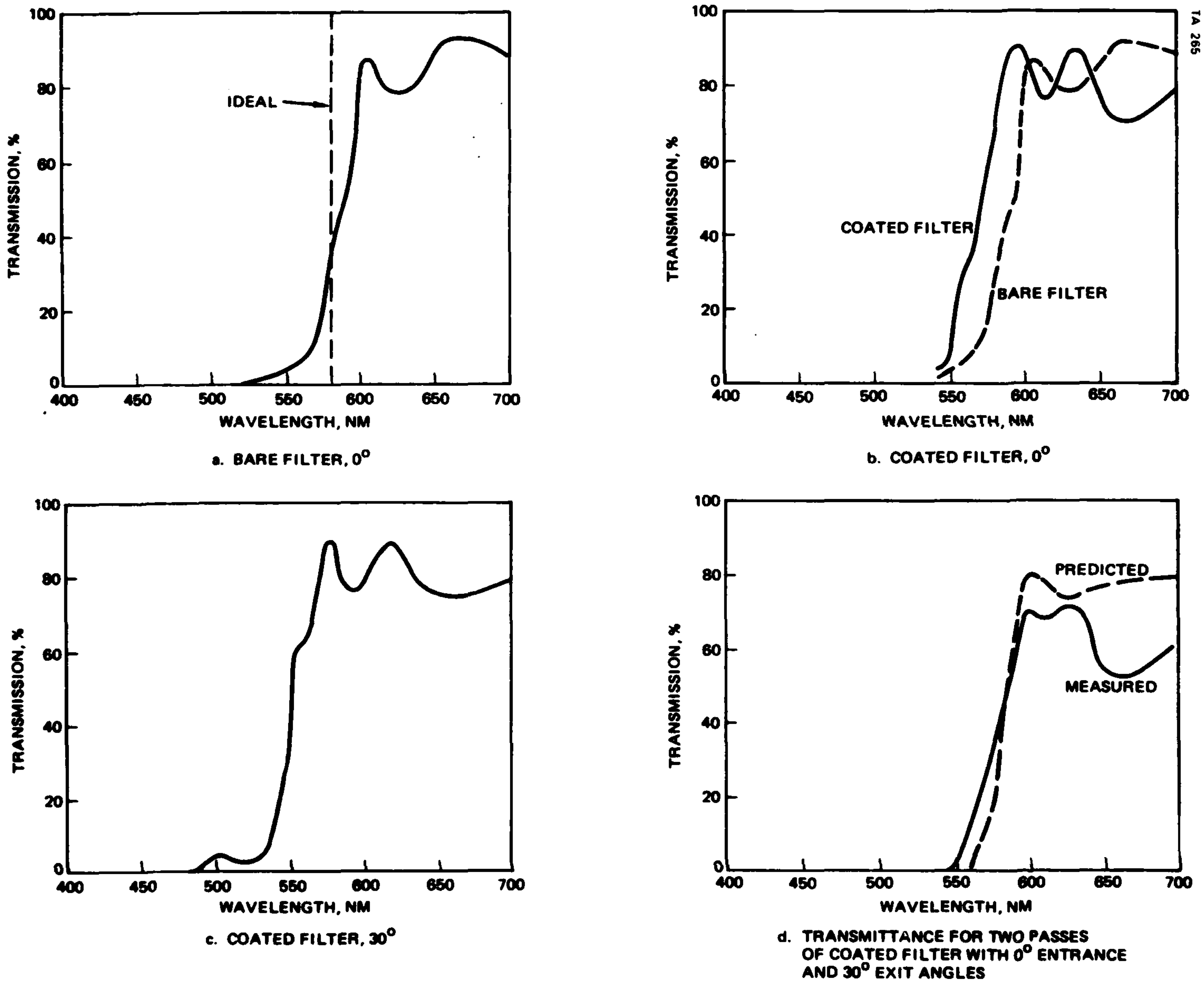

Figure 11. Spectral transmission of red filter stripe.

TABLE 4. MEASURED FILTER CHARACTERISTICS

	Predicted			Measured		
	R	G	B	R	G	B
Transmission, %	20	33	20	25	6	3
Dominant λ, nm	605	540	485	600	515	475
Purity, %	100	76	71	99	80	92

TABLE 5. PREDICTED DISPLAY PERFORMANCE WITH MEASURED FILTER CHARACTERISTICS

Color	Brightness 10^4 fc Ambient, fL	Contrast Ratio	Dominant λ, nm	Color Purity, %
Red	510	13.9	595	95
Green	150	4.1	525	65
Blue	93	2.5	475	70
Red + Green	623	17.0	590	95
Green + Blue	207	5.6	485	55
Red + Blue	567	15.5	495C	40
Red + Green + Blue	680	18.5	620	30
OFF (Black)	37	NA	620	30

DISPLAY PERFORMANCE

The final multicolor liquid crystal display was connected, using flat cables, to printed wiring boards containing video and sweep drive LSI circuits, as shown in Figure 12. These boards were, in turn, connected to, existing laboratory test equipment, including interface circuitry, power supplies, and a commercial alphanumeric symbol generator modified to produce multicolor characters. A collimated light source was positioned to provide illumination at a 30 degree incidence angle, and the display was viewed normal to its surface. Upon initial operation, it was apparent that the display did not provide the predicted performance. Red, Red + Green, Red + Blue, and Red + Blue + Green characters were clearly visible against a desaturated orange background. Additionally, the color differences between these combinations were apparent. When viewed from 30 inches, the Red + Green and Red + Blue characters appeared to be uniform in color, rather than composed of alternating color stripes. However, the Green, Blue, and Green + Blue characters were visible only with great difficulty and completely invisible at some viewing angles. While the predicted brightnesses and contrast ratios of Blue and Green characters were lower than those of Red characters, these colors still should have been clearly visible.

The first action taken to determine display performance was to measure the display on and off state reflectancies as a function of the illumination incidence angle. The test setup is shown in Figure 13. The measurements were taken three times: first, on a clean magnesium oxide diffuse reflectance standard to calibrate the equipment; second, on a typical black-and-white matrix LXD; and, third, on the multicolor display. The field of view of the photometer was adjusted to measure an area roughly 0.5 inch in diameter. Thus, the measured brightnesses were the average of the three color stripes. The expected values for the multicolor display reflectance in either the on or off states was the corresponding value for the black and white display multiplied by the average transmission of the three color filter (0.11 at 30 degrees incidence).

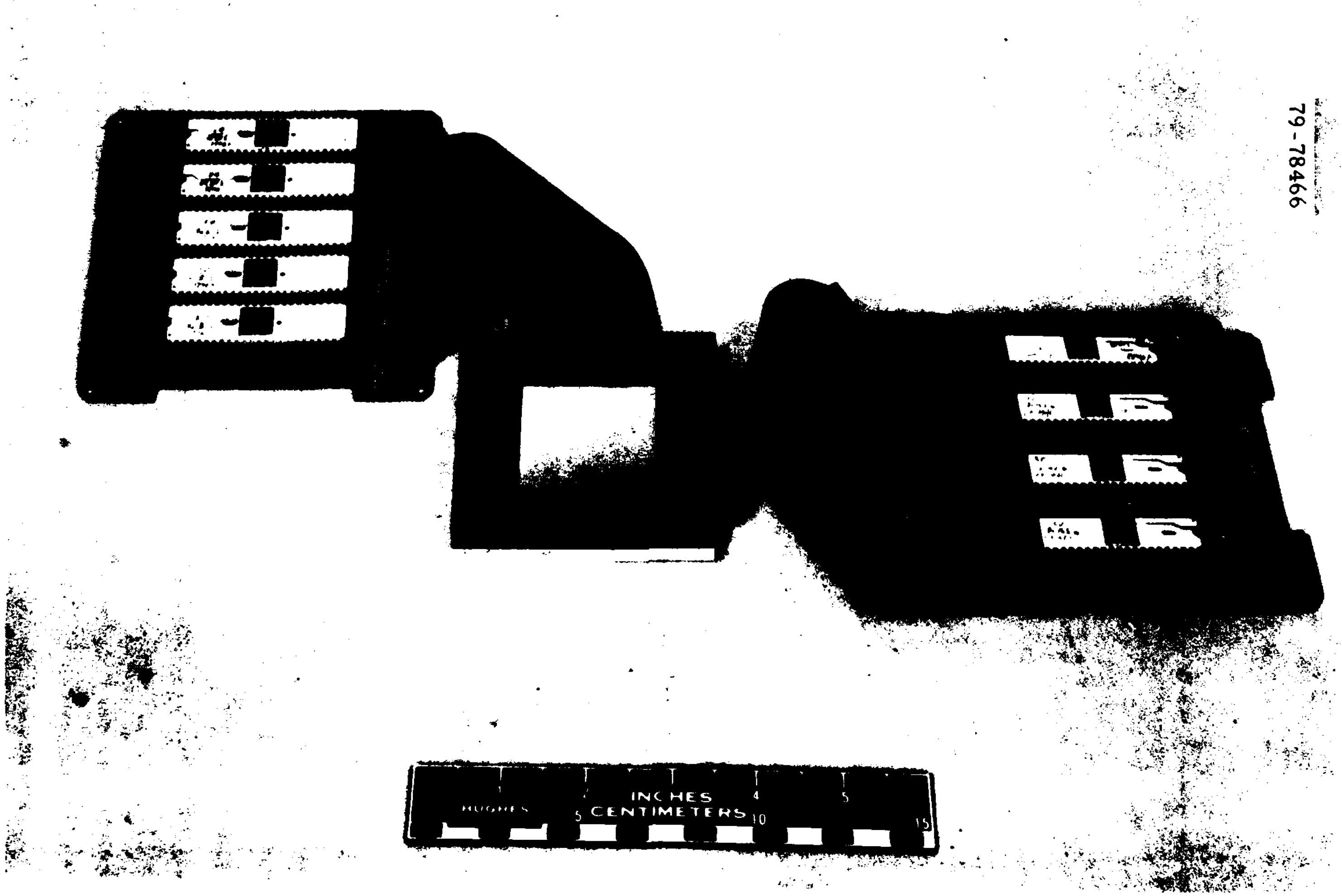

Figure 12. Multicolor Liquid Crystal Display and Drive Electronics

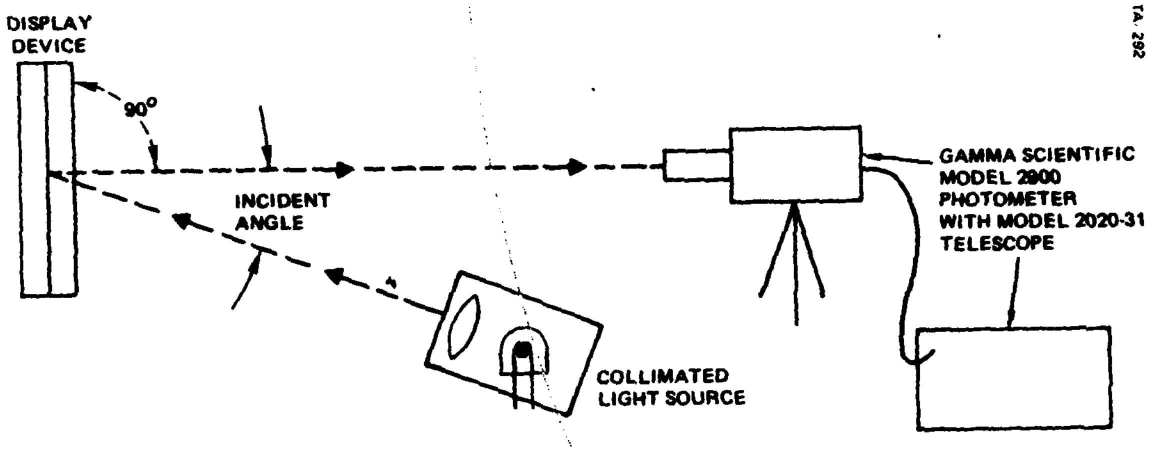

Figure 13. Average Brightness Measurement Setup

The results of these measurements are shown in Figure 14. The reflectance of the multicolor display in the off state (0 Volts applied to the LX layer) is 1.5 times that of the monochromatic display, or 16 times the predicted value. In the on state, (20 volts applied to the LX layer) the reflectance is roughly twice the expected level. The high diffuse reflectance of the multicolor display in both states indicated that the display contained a light scattering mechanism not contained in the monochromatic display.

A second set of measurements was made using a microscopic spot photometer to measure the reflectance of individual elements. The setup used is shown in Figure 15. The photometric microscope has a 0.0001 by 0.100 inch aperture which was aligned with its long axis parallel to the filter stripes. This aperture was then mechanically scanning across the stripes so that the reflectances of the Red, Green, and Blue elements could be determined independently. The measured results are given in Figure 16 for six typical stripes. The average reflectances measured in both states are consistent with the previous measurements at an incident angle of 45°. Since the high off-state reflectance varies in proportion to the striped filter transmissions for each color, this data indicates that the light scattering mechanism is located behind the filter. The contamination prevention barrier was suspected because it is the only material behind the filter not

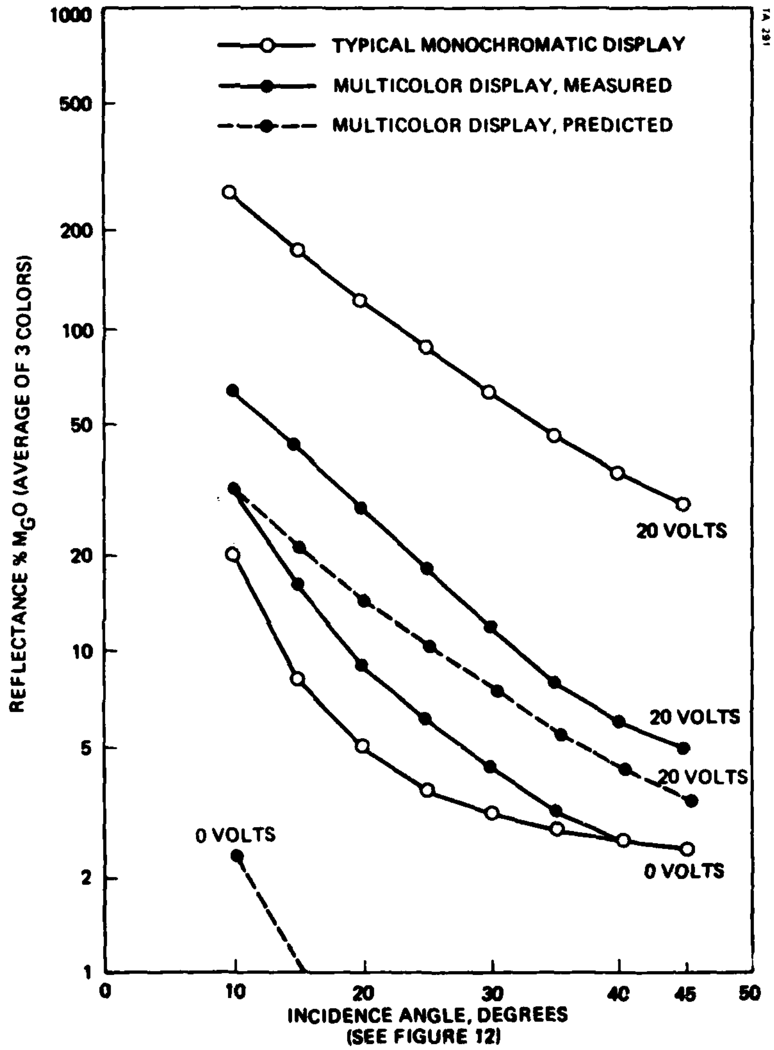

Figure 14. Multicolor Display Scattering Performance

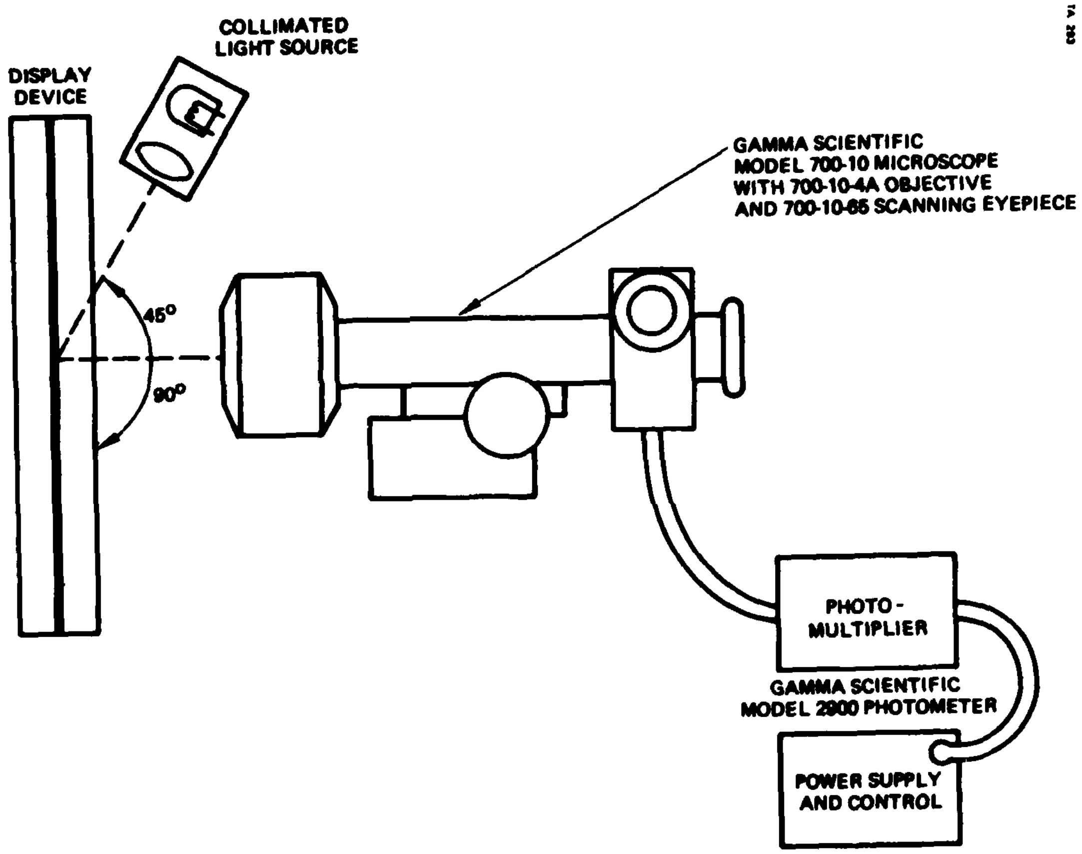

Figure 15. Spot Brightness Measurement

contained in the monochromatic display. This suspicion was subsequently confirmed by microscopic evaluation of the remaining three color filters, which had an identical barrier layer.

The logbooks for the equipment used to deposit the contamination prevention barrier were checked and an error in the process discovered. While the sputtering parameters (system pressure, substrata temperatures, deposition rate, etc.) used were correct, the wrong source had been placed in the machine and the wrong material was deposited. Moreover, the material actually deposited was totally imcompatible with the sputtering parameters used. Thus, the resulting barrier layer was very porous and full of bubbles. While it did, apparently, prevent contamination of the liquid crystal material, the included bubbles scattered the incident light and reduced the display device contrast.

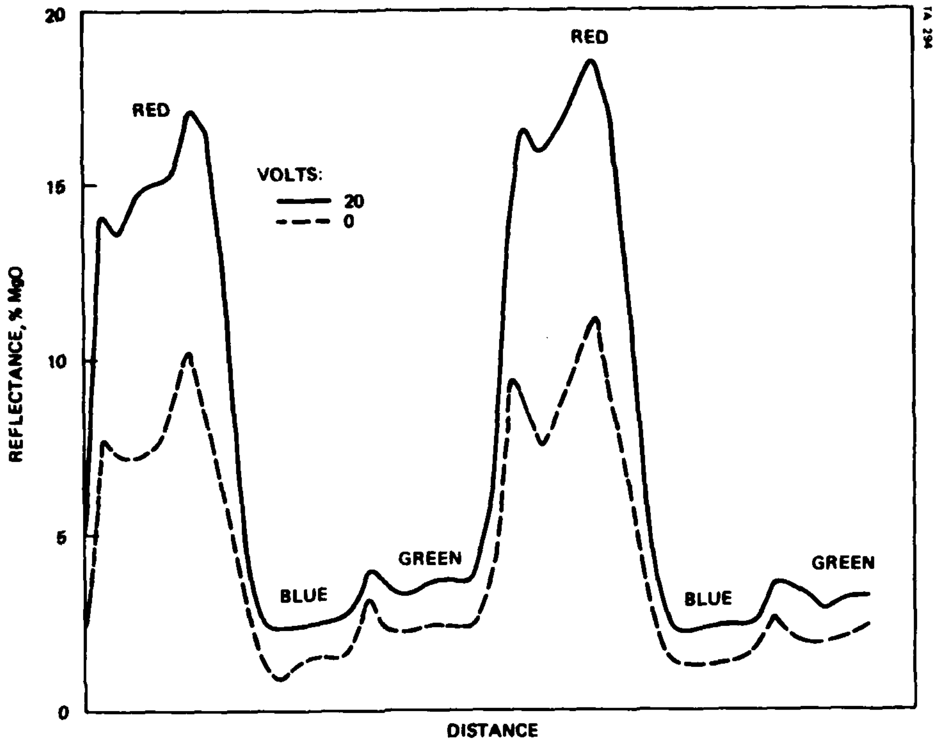

Figure 16. Spot Brightness

The on and off state reflectances of the individual colors were determined for 45 degree incidence from the data in Figure 16. They were then extrapulated to 30° incidence using the data of Figure 14. The performance of the display was then calculated for comparison with the previously discussed predictions. The performance is summarized in Table 6.

TABLE 6. DISPLAY PERFORMANCE CALCULATED FROM MEASURED REFLECTANCE VALUES

Color	Brightness 10^4 fc Ambient, fL	Contrast Ratio	Dominant λ, nm	Color Purity, %
Red	1620	1.59	610	50
Green	1080	1.06	610	20
Blue	1100	1.08	535C	30
Red + Green	1680	1.65	595	50
Green + Blue	1160	1.14	550C	20
Red + Blue	1700	1.67	500C	25
Red + Green + Blue	1760	1.73	495C	20
OFF (Black)	1017	NA	495C	20

SECTION 4

CONCLUSION AND RECOMMENDATIONS

Although three independent, totally solvable, problems combined to limit the performance of the Multicolor Alphanumeric Display devices constructed on this program, the basic display concept has been demonstrated. The existence of the technology required to make the striped color filters has been proven. Additionally, the use of the striped format to produce asthetically pleasing primary and secondary (i. e. combinging Red and Green to produce yellow) colored alphanumeric symbols was successful. Thus, we recommend that this effort be continued, and that redesigned display devices be constructed to fully demonstrate the capabilities of this technology. The following improvements should be incorporated:

1. The desired filter transmission characteristics should be re-evaluated to allow for the fact that ambient light enters and exits the display at different incident angles. The filter transmission characteristics measured on the present program can be applied to the desired characteristics to determine the necessary transmissions at normal incidence. Additionally, the tolerances on the filters specified to the manufacturer must be tightened and additional time allowed to ensure the filters produce the desired display colors.
2. The contamination prevention barrier using the correct materials must be proven with test (non-matrix) display cells. Additionally, each three-color filter should be evaluated after barrier deposition but before display assembly.
3. The striped-filter multicolor display concept should be combined with a proprietary non-light trap liquid crystal display technique. This technique provides high contrast with diffuse ambient illumination and eliminates the requirement that the display be illuminated at a specific viewing angle.
4. If application requirements allow, the blue filter stripes should be eliminated, resulting in a display which can provide 8 rows of 12 characters in red, yellow, or green colors. Each character would

be 0.14 inches in height. The reason for eliminating blue is because the chromaticity coordinates of the blue color have a large Z component, while the coordinates of the red and green have Z values near 2cvo. Thus the colors produced by only the red and green stripes (including stray scattering in the *off* states) move along the $X + Y = 1$ line on a chromaticity diagram. This line is the locus of 100% purity red, yellow, and green colors. However, the Z component produced by the blue elements in the off state is sufficient to reduce the purity of the red, yellow, and green colors by 20 to 30 percent. Additionally, when the red and green filter transmission characteristics are chosen to provide a saturated yellow color in combination, the red + blue and green + blue combinations have low saturation and little utility. Finally, the blue filter transmission is most sensitive to angular shifts and acceptable brightness and color purity are very difficult to achieve simultaneously.

In conclusion, we believe that one additional development effort will be sufficient to demonstrate a multicolor (red, green, yellow) matrix liquid crystal display with performance in excess of any other multicolor display technology and the capability of fulfilling advanced cockpit command-and-control display requirements.